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IONOSPHERIC MODIFICATION WITH OBLIQUELY INCIDENT WAVES: ELECTRON HEATING AND PARAMETRIC INSTABILITIES

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The nonlinear processes that lead to ionospheric modification divide naturally into two categories: (1) ohmic heating, which alters temperature and hence, reaction rates, collision frequencies, and particle densities, and (2) generation of parametric instabilities, which causes a myriad of phenomena.

As the incidence angle is increased, heating is affected by two competing trends. It is weakened by the increased path length, but is strengthened near caustics. (over)

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Obliquely incident waves cannot satisfy frequency-matching conditions required for generation of the parametric decay instability. Therefore, a number of effects produced by vertical modifying waves, which can satisfy the frequency matching conditions, cannot be produced by oblique waves. Such effects include wide-band absorption and aspect-sensitive scattering from short-scale, field-aligned striations. However, oblique waves might be capable of producing artificial spread-F.

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PARAMETRIC INSTABILITIES

SUMMARY

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As the incidence angle is increased, heating is affected by two competing trends. It is weakened by the increased path length, but is strengthened near caustics. A transmitter with a power-gain product on the order of 10 MW can launch an oblique wave strong enough to produce electric fields of several tenths of a volt per meter or more in the ionosphere. Such fields produce substantial temperature increases, which are initially concentrated near the caustics, but spread via heat conduction. Within a few tens of seconds, the temperature of a volume having a dimension of about 50 km can be increased by a few hundred degrees. Heating is more effective at night than in the daytime. An HF signal that traverses such a heated region will undergo changes in amplitude and angle-of-arrival that are detectable on the ground.

Obliquely incident waves cannot satisfy frequency-matching conditions required for generation of the parametric decay instability. Therefore, a number of effects produced by vertical modifying waves, which can satisfy the frequency matching conditions, cannot be produced by oblique waves. Such effects include wide-band absorption

and aspect-sensitive scattering from short-scale, field-aligned striations. However, oblique waves might be capable of producing artificial spread-F.

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I. INTRODUCTION

The propagation of an electromagnetic wave in the ionosphere is a nonlinear process. The ionosphere, through its refractive index, alters the wave; and the wave, through various mechanisms, alters the ionosphere. Phenomena caused by the action of a strong wave on the ionosphere include electron and ion heating, increases or reductions in charged particle densities and collision frequencies, and production of structured irregularities in the ionospheric refractive index.

In practice, most radar or communication systems transmit signals that are too weak to modify the ionosphere substantially. Linear theory, which includes only the action of the ionosphere on the wave, is used to analyze their performance. However, during the past 15 years a number of powerful high-frequency (HF) radio transmitters have been developed solely to transmit waves strong enough to produce measurable nonlinear effects in the ionosphere. At first, it was hoped that detectable ionospheric heating might occur, therefore these early tests were called heating experiments. Because so many types of nonlinear effects, including heating, were observed, such tests are now described by the more general term, ionospheric modification experiments. The terms heating and modification are used interchangeably in this report.

Summaries of the phenomena observed in modification experiments are given in reviews by Gurevich,[1] Utlaut and Violette[2] and Duncan and Gordon.[3] Several of those phenomena could influence the performance of military systems. However, virtually all ionospheric modification experiments have been carried out with the powerful modifying wave at vertical incidence, whereas geographic constraints on military applications dictate that the modifying wave be at oblique incidence. Moreover, for reasons given below, it is not obvious that the effects produced by a vertically incident modifying wave could be produced by one that is obliquely incident.

This present report identifies nonlinear phenomena that could (1) be caused by obliquely incident modifying waves, and (2) influence the performance of friendly or enemy military systems. For those reasons it is helpful to categorize the nonlinear wave or modifying wave--in terms of it altering the propagation of some communication or radar signal--the wanted wave. That alteration might be either favorable or unfavorable. In certain instances the wanted wave might be so powerful that it is also the modifying wave. We will call that situation self-action or, more realistically, self-limitation.

The nonlinear processes that lead to ionospheric modification divide naturally into two categories: (1) simple heating, which alters temperature and hence, reaction rates, collision frequencies, and particle densities, and (2) generation of parametric instabilities, which causes a myriad of phenomena which will be discussed in later sections. Both categories can drastically change the amplitude, phase, or path of a signal that traverses the modified region, and both depend strongly on the incidence angle of the modifying wave.

As the incidence angle is increased, heating, which is proportional to the local power density, is affected by two competing trends. The field is weakened by the increased path-length, but it is strengthened near caustics. The results of this report determine whether field concentration near caustics overcomes the geometric spreading suffered by oblique modifying waves. Certain parametric instabilities cannot be excited by oblique waves because only vertical waves can reach heights where matching conditions on frequency are met. The phenomena that do and do not depend on meeting such matching conditions are also examined in this report.

In Section II the electron temperature change in the F-layer that could be achieved with an oblique modifying wave is calculated. Several manifestations of parametric instabilities known to be excited by vertical modifying waves as well as those that might be excited by an oblique wave are discussed in Sec. III. The significance of a Soviet modification experiment that used an oblique wave is discussed in Sec. IV, and Sec. V lists the conclusions drawn from our data.

II. ELECTRON HEATING

Heating affects radar or communication systems in a number of ways, depending on the wave frequency and the region of the ionosphere in which the heating occurs. The most obvious effect is on the electron collision frequency, which depends on temperature. Heating also alters the charged particle densities and hence, the refractive index.

In the lower ionosphere the most important collisions are the ones that occur between electrons and molecules. The electron-molecule collision frequency is proportional to the squareroot of the electron temperature. The main effect of heating in the lower ionosphere is the increase in electron collision frequency and thus the absorption of HF and very high frequency (VHF) waves. One result of this phenomena is self-absorption, where increasing the power of the incident wave does not produce a commensurate increase in the power of the reflected wave. In extreme cases, an *increase in* transmitter power can actually cause a decrease in the intensity of the received signal.[1]

In the F-layer, the coulomb collisions between electrons and ions are the most important ones, the electron collision frequency is inversely proportional to the electron temperature, raised to the three-halves power. Here heating reduces the F-layer collision frequency. This F-layer heating does not affect the absorption of HF waves very much. It can affect ray trajectories because the heated volume expands, causing a local reduction in electron density. The strongest heating occurs near reflection points and caustics, where the wave is strongest and is most sensitive to changes in density. This tendency gives a layered structure to the electron density.

In order for any of the above phenomena to occur, the modifying wave must cause a substantial rise in electron temperature. There is no question that such changes are caused by powerful vertically incident modifying waves. It is not obvious that oblique waves, which undergo much more spherical spreading than vertical waves, can supply

a power-density to the ionosphere high enough to cause the desired temperature changes.

In this report, the amount of heating that an oblique wave will cause in the ionosphere is calculated. Also studied is whether or not that heating will produce effects that are detectable on the ground. Although the ultimate goal is to ascertain the military implications of such effects, the emphasis here is to determine if an experiment using an oblique modifying wave would yield positive results.

The first step is to calculate the electric fields delivered to the ionosphere by the oblique modifying wave. We then estimate the change in electron density produced by those fields.

CALCULATION OF FIELDS IN IONOSPHERE

The rate of ionospheric heating is proportional to the square of the electric field in the ionosphere. Calculation of that field is more complicated for an oblique wave than for a vertical wave because the strongest fields occur in caustic regions, where ray tracing is *invalid*.

Fortunately, a computer code is available for calculating HF/VHF fields in regions of strong focusing, including caustics and cusps. That method, described by Warren, DeWitt, and Warber,[4] uses ray intercept data provided by standard ray-trace programs as inputs to calculations of fields in regions where ray-density calculations fail. It extends the usefulness of ray-trace calculations to precisely the ionospheric regions that are critical to the results of the present report.

The fields depend on the wave frequency, path-length, transmitter pattern and power, and ionospheric conditions. An analysis of the dependence of all those parameters is beyond the scope of the present feasibility study. Instead, sample calculations for realistic nominal conditions are presented.

Our calculations are normalized to a radiated power of 100 kW and assume a transmitting antenna gain (see Fig. 1). Those gains are typical of rhombic antennas in current use. The assumed model

ionospheres shown in Fig. 2, represent day and night midlatitude conditions along a north to south propagation path. Figure 3 illustrates a sample ray trace based on Figs. 1 and 2. Note that the caustics occur beyond the midpoint of the propagation path.

We calculate the fields in most regions of the ionosphere directly from ray densities, such as those shown in Fig. 3. We then use the coder developed by Warren, DeWitt, Warber[4] to extend those calculations into the strong focusing regions. The resulting electric field contours for daytime conditions are illustrated in Figs. 4 through 6 and the nighttime conditions in Figs. 7 through 9. It can be determined from Figs. 4 through 6 that during the daytime the focused region is about 500 km long and occurs between altitudes of about 160 and 210 km. Changing the frequency by 1 MHz causes the contour pattern to move about 70 km laterally. The strongest fields occur in two regions, which correspond to the internal and external caustics. Figure 6, which gives results for a frequency of 18 MHz, illustrates a cusp at a range of 1150 km and an altitude of 260 km. The maximum fields lie near the internal caustic.

Figures 7 through 9 reveal that the focused region occurs at higher altitudes (220 to 310 km) at nighttime than in the daytime. As expected, higher frequencies are preferred at night. The position of the contour pattern is more sensitive to frequency changes at nighttime than in the daytime--an 0.5 MHz frequency change moves the pattern laterally about 150 km. As in the daytime field patterns, the nighttime field patterns exhibit internal and external caustics. However, no cusps are present at night.

The results illustrated in Figs. 4 through 9 can be extended to radiated powers other than 100 kW by noting that the electric field is proportional to the square root of the radiated power. These results were calculated using linear theory; therefore, self-action is not included.

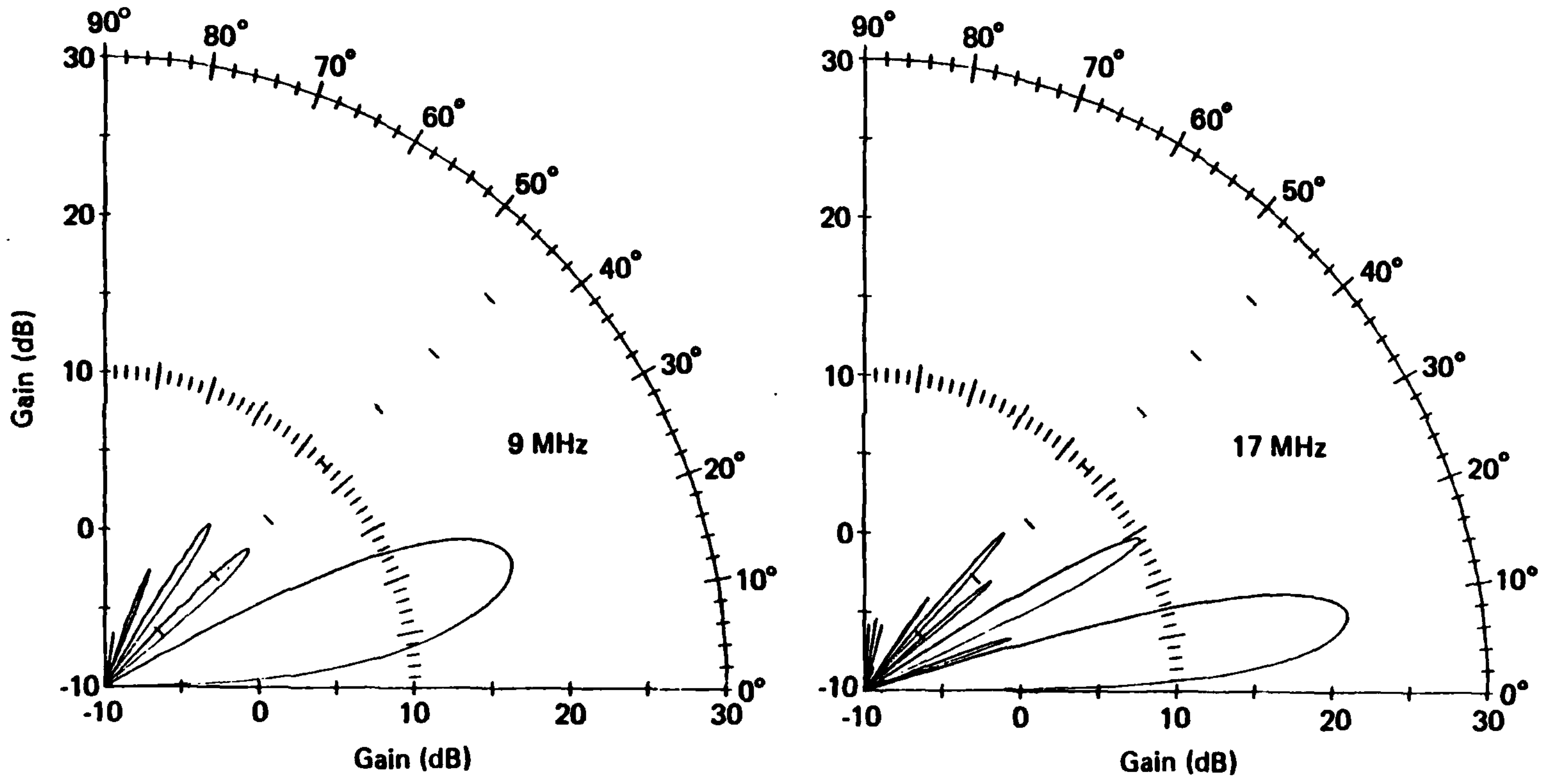


Figure 1. Vertical antenna pattern assumed for calculation of electric fields.

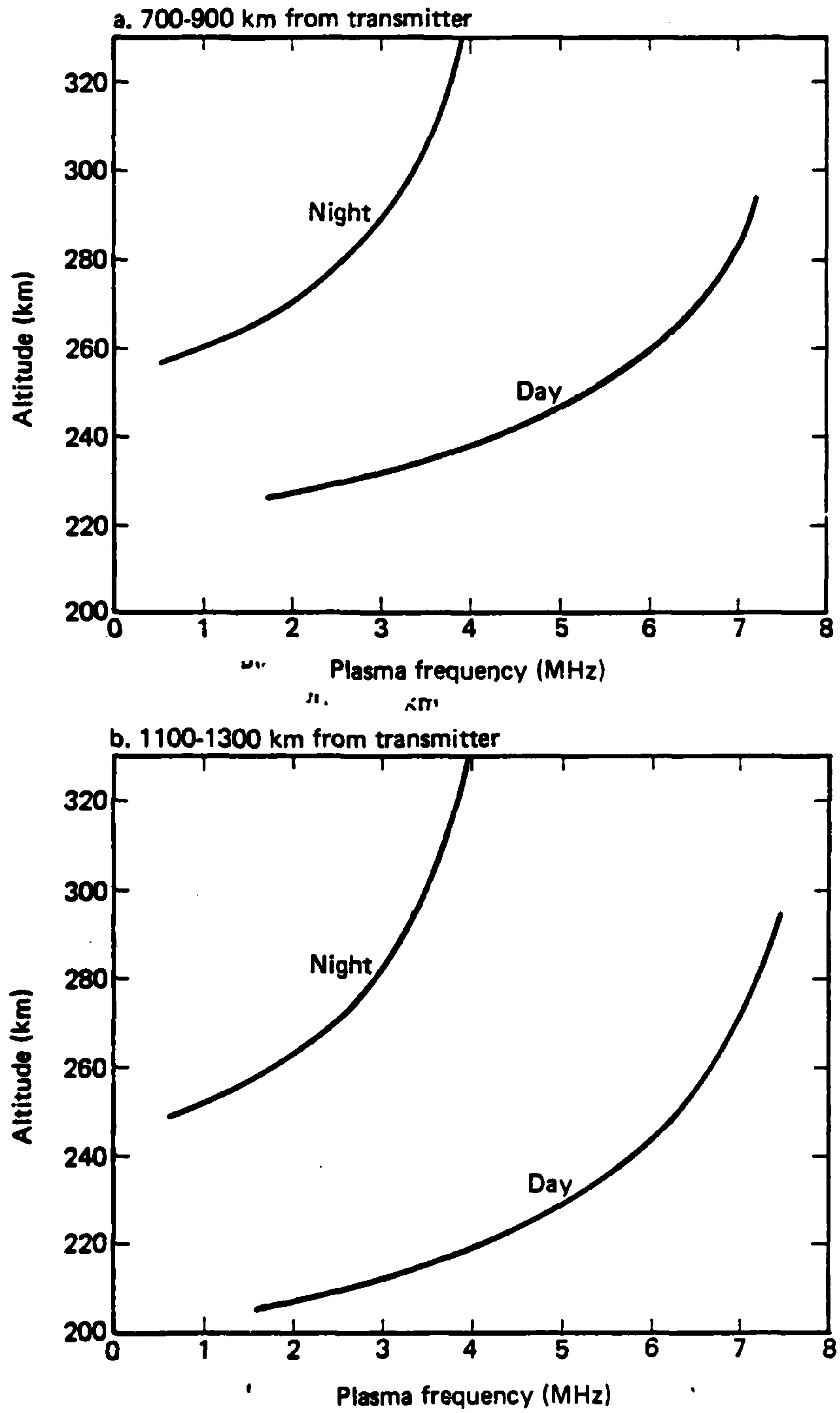
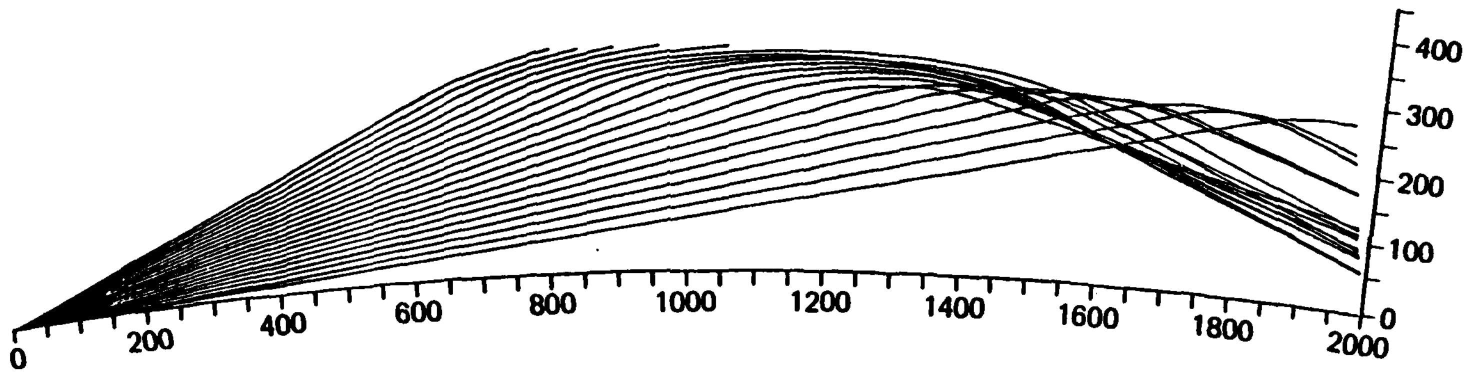


Figure 2. Ionosphere profiles for calculation of electric fields.



Note: See Fig. 2 for ionosphere profiles.

Figure 3. Sample ray trace for nighttime ionosphere; frequency = 9.5 MHz, geomagnetic field ignored.

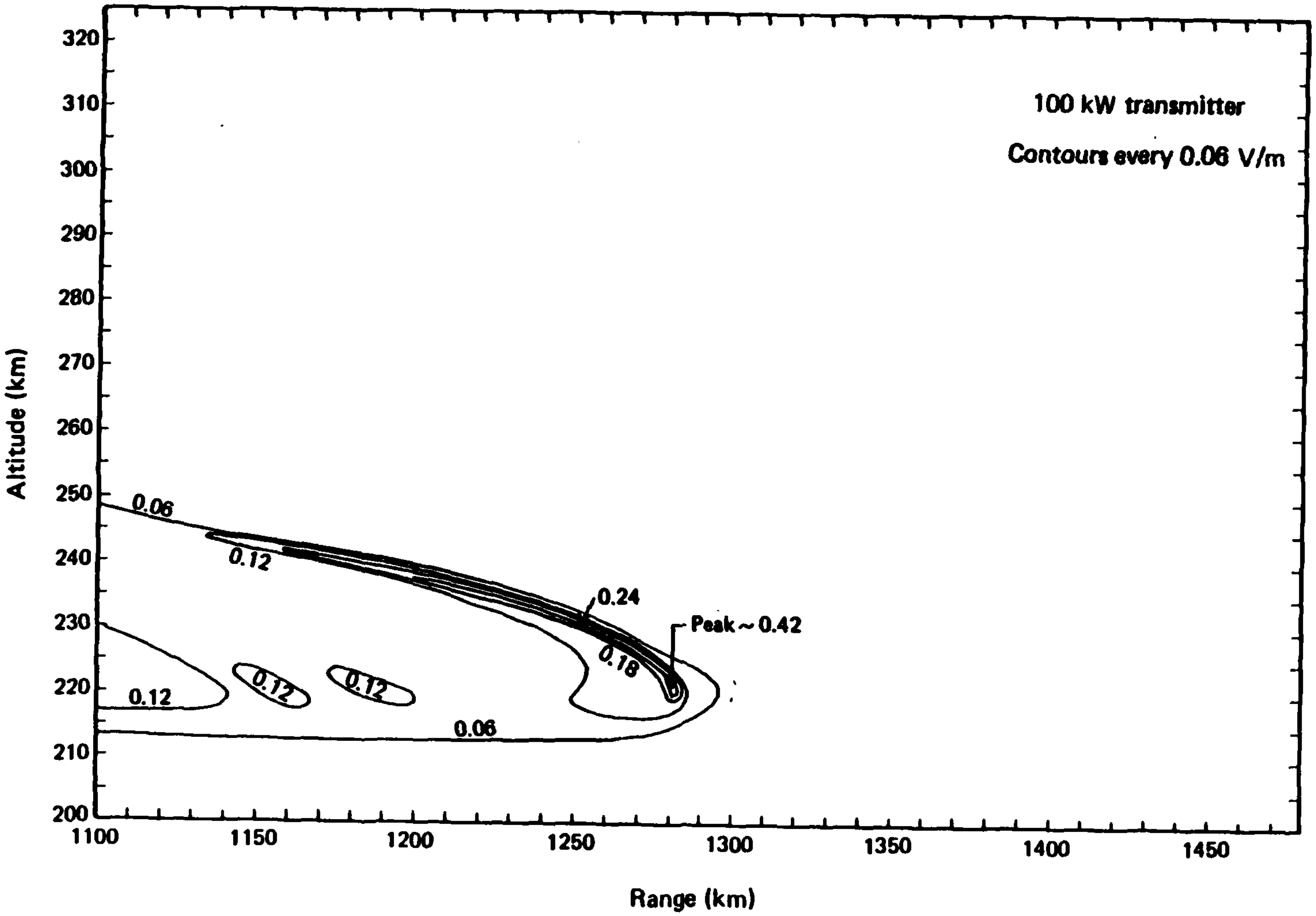


Figure 4. Daytime electric field contours; frequency = 16 MHz.

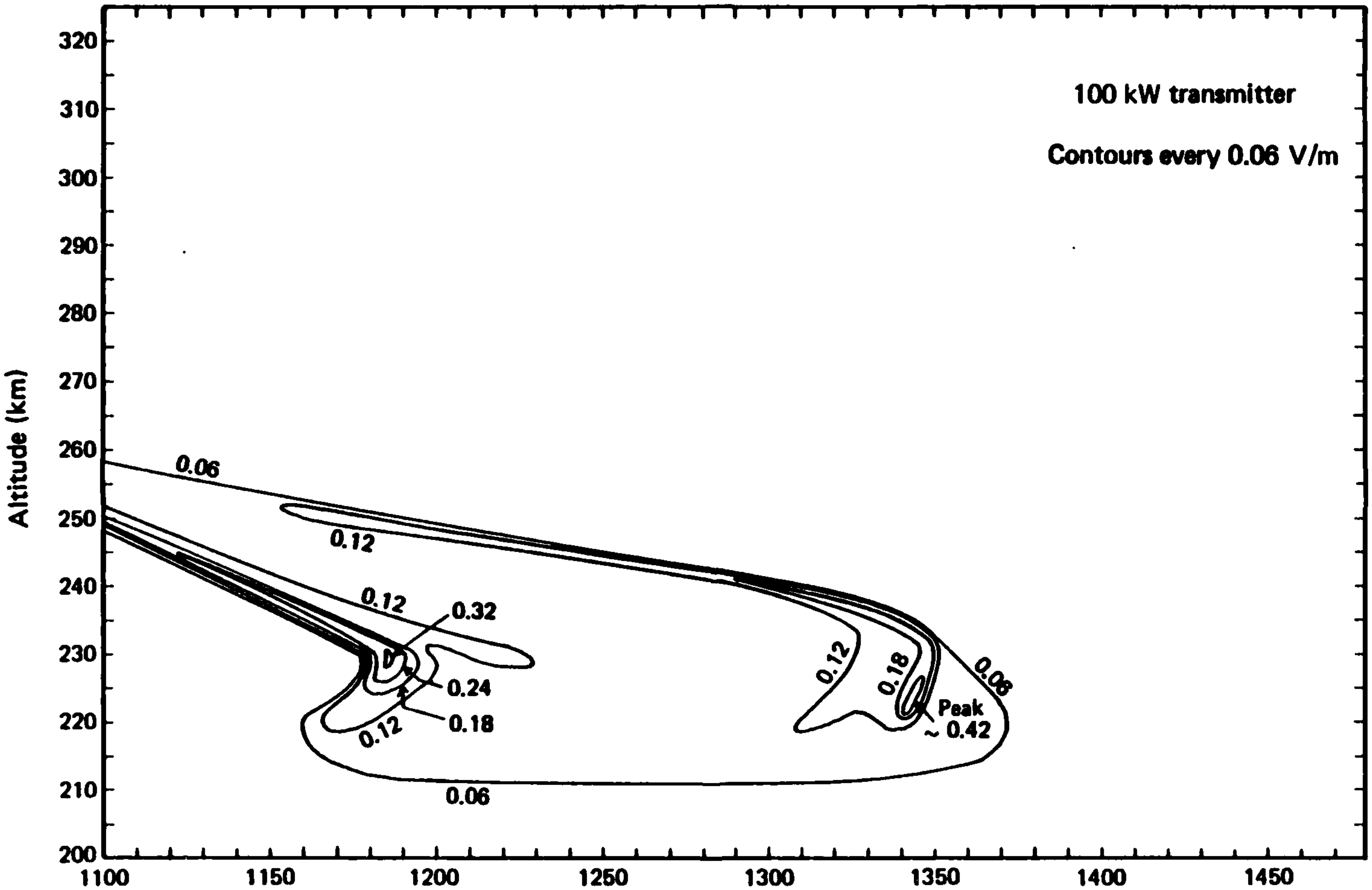


Figure 5. Daytime electric field contours; frequency = 17 MHz.

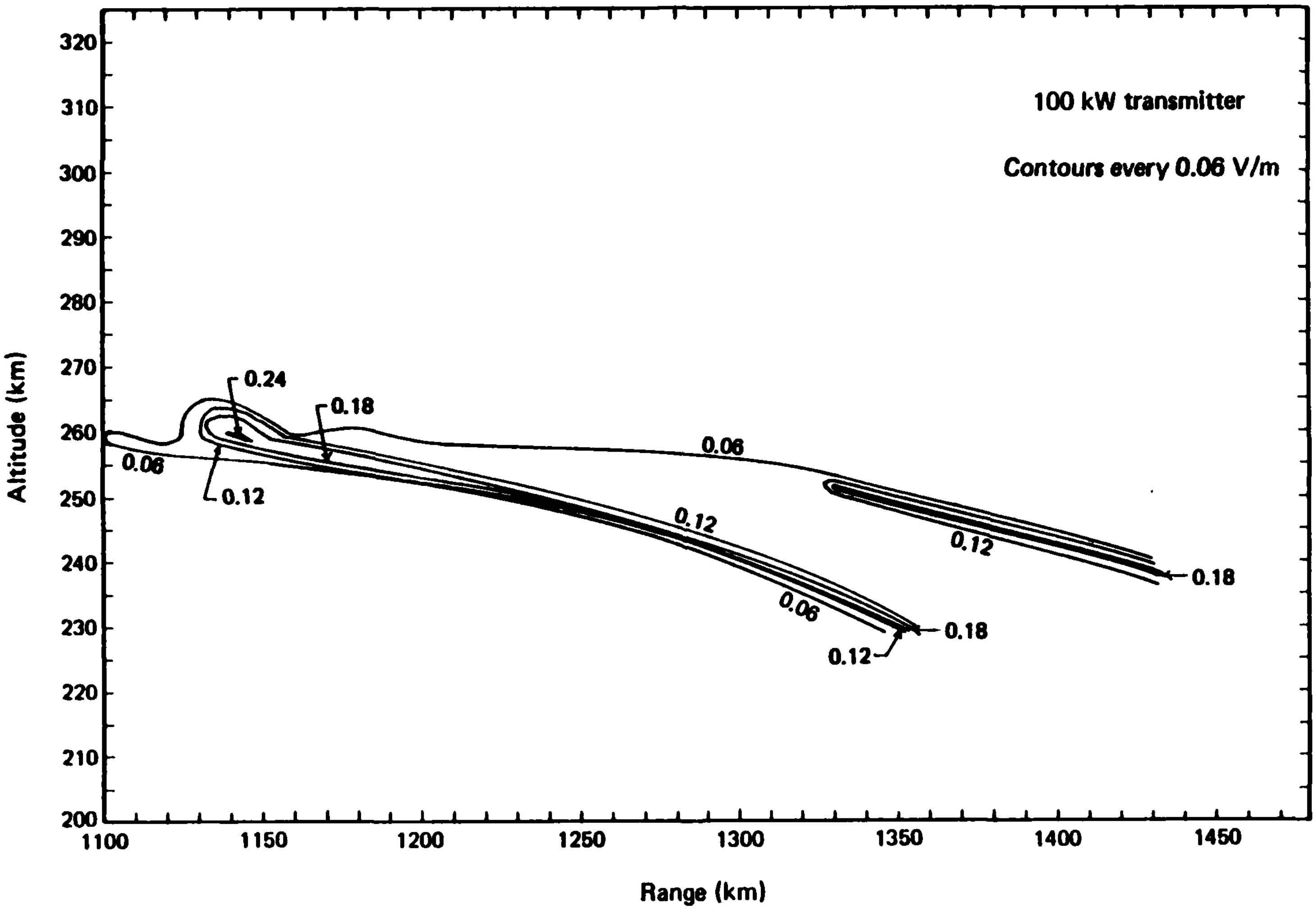


Figure 6. Daytime electric field contours; frequency = 18 MHz.

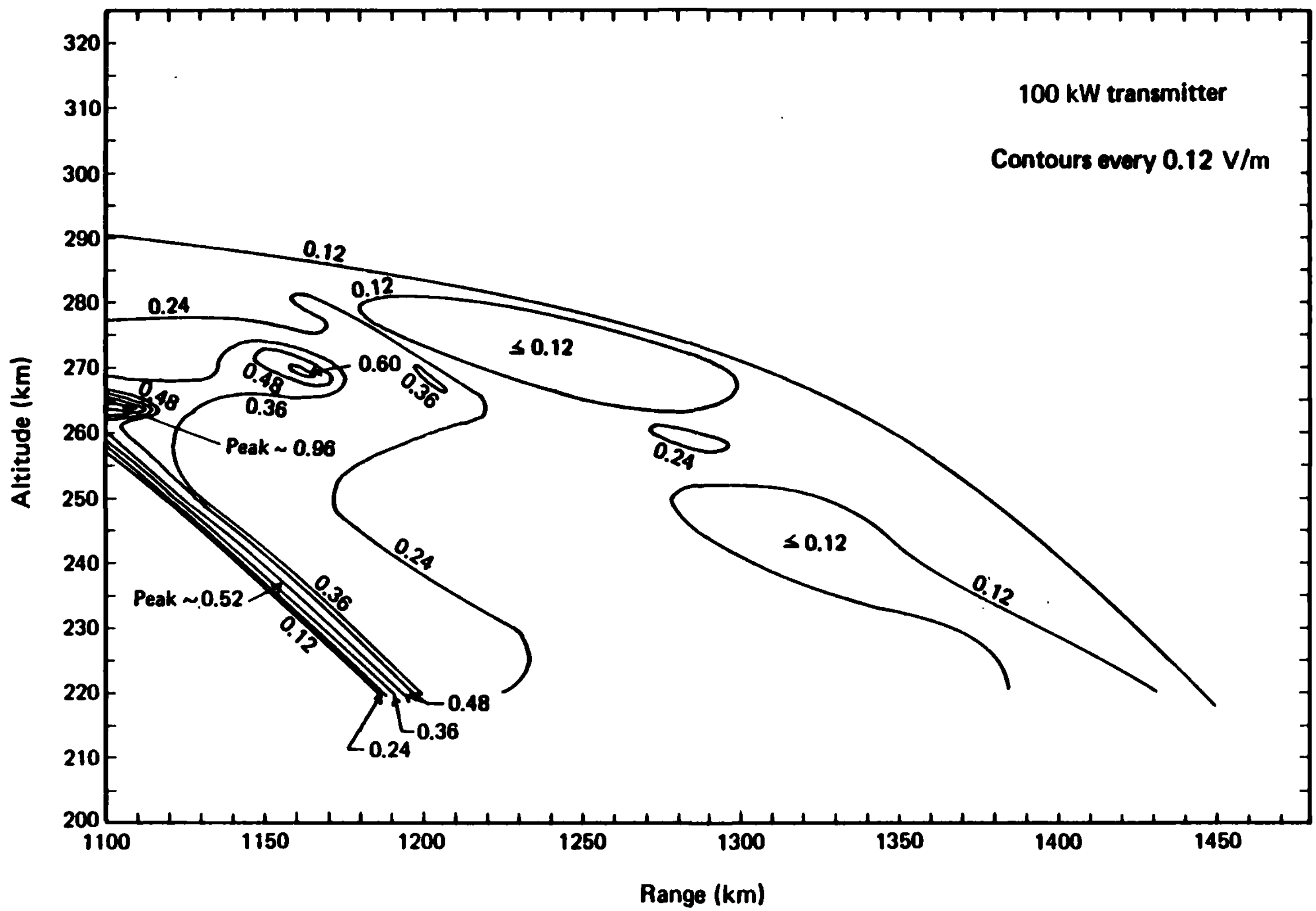


Figure 7. Nighttime electric field contours; frequency = 8.5 MHz.

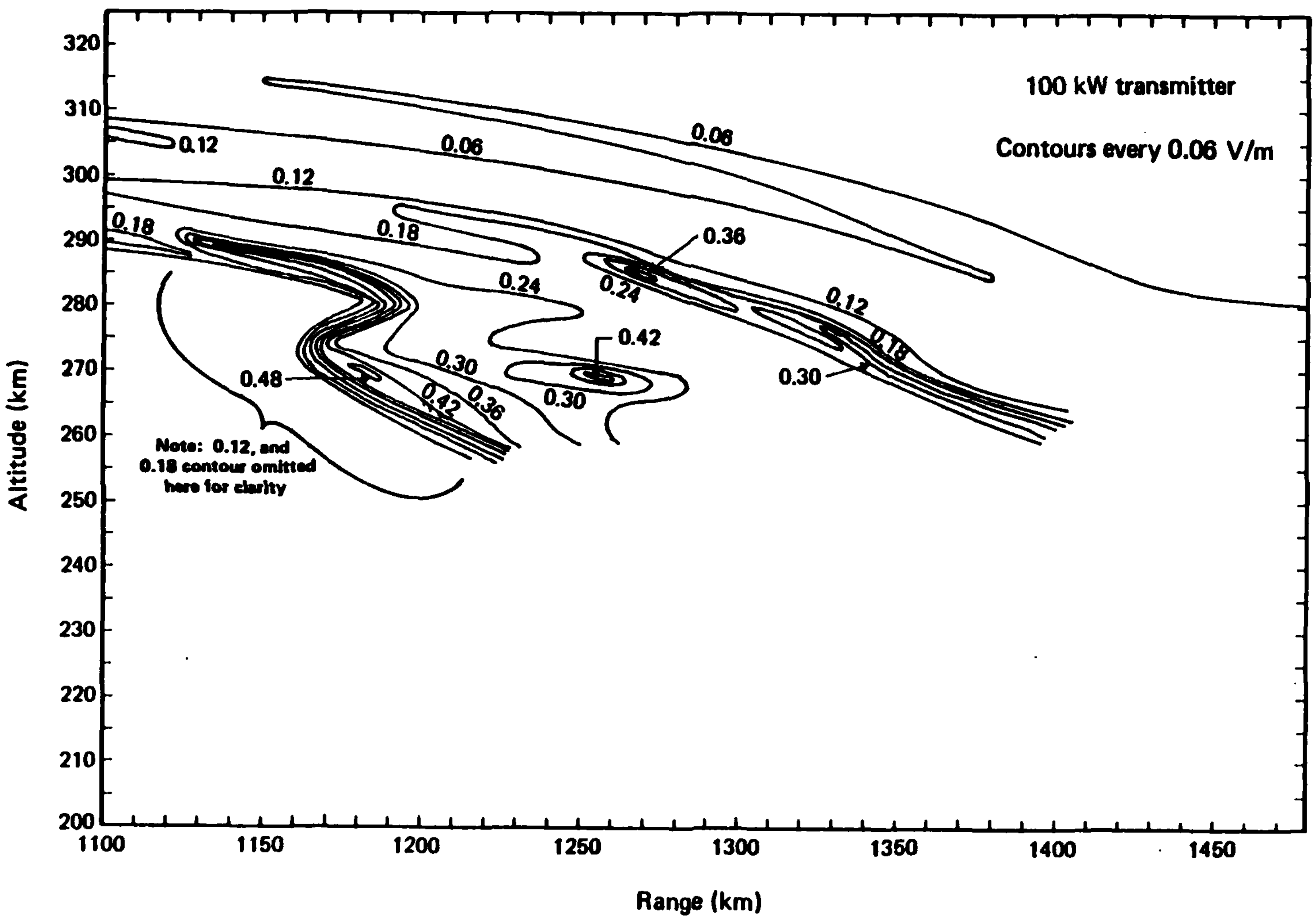


Figure 8. Nighttime electric field contours; frequency = 9 MHz.

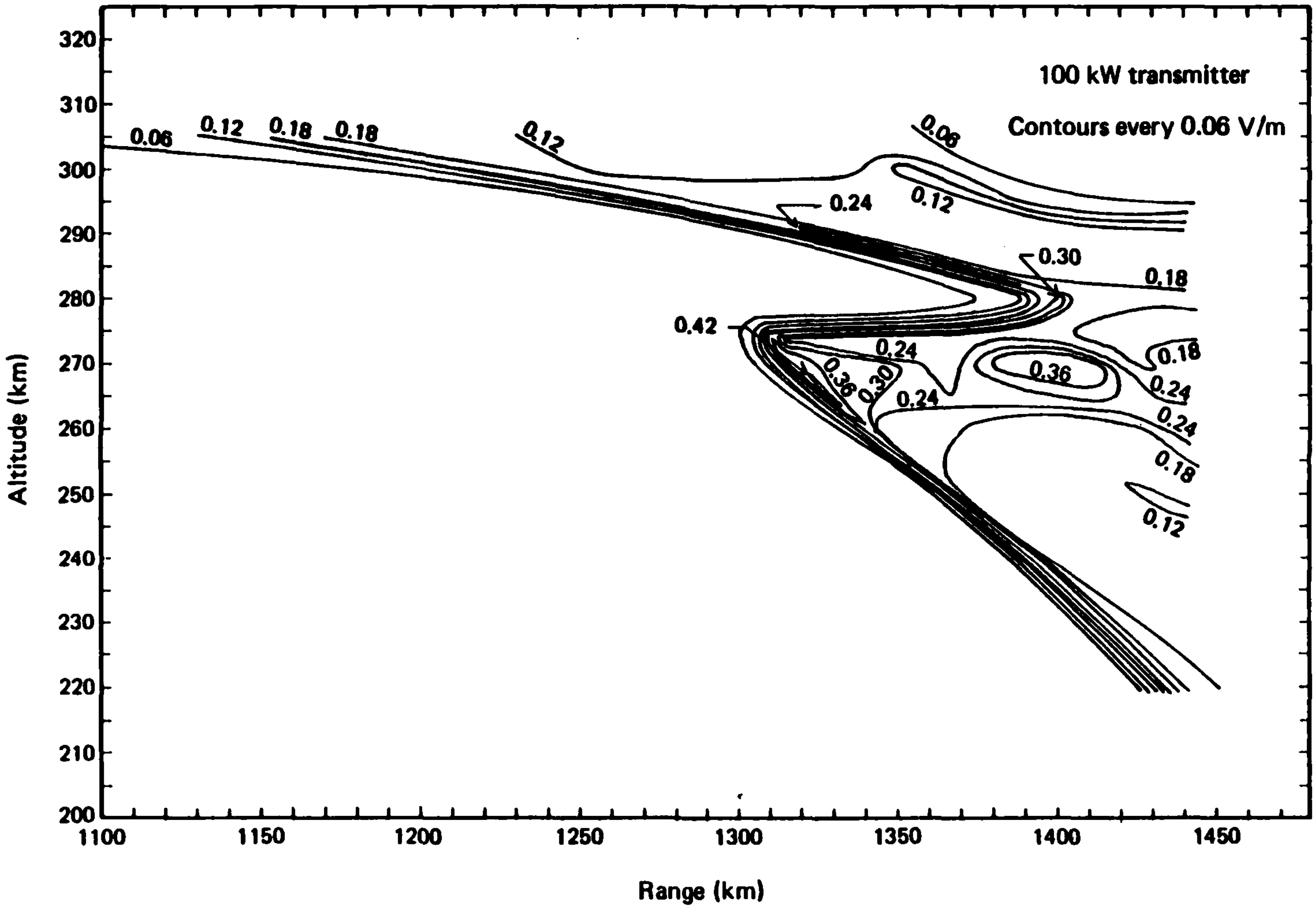


Figure 9. Nighttime electric field contours; frequency = 9.5 MHz.

CALCULATION OF ELECTRON TEMPERATURE CHANGES

A full-fledged calculation of the temperature changes caused by the electric fields shown in Figs. 4 through 9 should account for transport processes. This requires a numerical analysis as extensive as the one that was used to calculate the fields themselves. Mantas, Carlson, and LaHoz[5] present the results of such an analysis, performed to make detailed comparisons with measured temperature changes produced by the powerful Arecibo HF heater. Fortunately, high accuracy is not needed for the present feasibility analysis. Semiquantitative calculations are adequate for determining if the heating produced by an oblique modifying wave has manifestations that could be sensed on the ground. We will calculate the heating that would occur in the absence of transport processes, and then estimate the extent to which transport would alter the results obtained.

In the absence of diffusion or heat conduction, the electron temperature is described by the following equation:

$$\frac{dT}{dt} = \delta\nu T_0 \left[\frac{E^2}{E_p^2} - \frac{(T - T_0)}{T_0}\right] , \tag{1}$$

where

$$E_p^2 = \frac{3KT_0 m\delta\omega^2}{e^2} , \tag{2}$$

and E_p is the characteristic plasma field as in Gurevich,[1] E is the electric field of the modifier wave, T is the electron temperature, T_0 is the ambient electron temperature, δ is the fractional energy lost by an electron per collision, ν is the electron collision frequency, ω is the wave angular frequency, m is the electron mass, and K is Boltzman's constant. In work done by Gurevich[1] and Walker,[6] Eqs. (1) and (2) are derived and discussed.

Regardless of the form of the collision frequency ν , the steady-state solution of Eq. (1) is

$$\frac{T - T_0}{T_0} = \frac{\Delta T}{T_0} = \frac{E^2}{E_p^2} . \tag{3}$$

Therefore, the maximum possible fractional change in electron temperature is simply the ratio of the square of the wave electric field to the characteristic plasma field. In the absence of transport processes, the form of the collision frequency governs only the time required to achieve the maximum temperature change given by Eq. (3).

The collision frequency depends on temperature and on the electric field E. That dependence causes Eq. (3) to be nonlinear and therefore, impossible to solve analytically. Before presenting numerical solutions to Eq. (3), it is helpful to discuss analytic solutions obtained in the weak-field limit, where the collision frequency is approximately constant throughout the heating process. For that limiting case $\nu(T) = \nu_0(T_0)$, and Eq. (3) is simply a first-order linear equation whose solution is

$$\frac{\Delta T}{T_0} = \begin{cases} \dfrac{E^2}{E_p^2} \left[1 - \exp\left(-t/t_0\right)\right] & \text{for heater on,} \quad (4a) \\[2ex] \dfrac{E^2}{E_p^2} \exp\left(-t/t_0\right) & \textit{for heater off,} \quad (4b) \end{cases}$$

where

$$t_0 = 1/\delta\nu_0 \quad . \tag{5}$$

The quantity t_0, given by Eq. (5), is a characteristic heating time required to achieve most of the temperature change. More simply, the modifying wave should be transmitted for a time that exceeds t_0.

We now account for the dependence of the collision frequency on temperature. In strong fields T(t) will exceed T_0, and will change markedly over the heating period. In the lower ionosphere the collision frequency increases with the rise in temperature; whereas in the F-layer where electron-ion collisions dominate, the collision frequency decreases. The electric field is strongest near the caustics, which occur mainly in the F-layer (see Figs. 4 through 9). Most of the heating occurs in the F-layer also. We therefore use the following

dependence for collision frequency on temperature:

$$\nu(T) = \nu_0(T_0)\left[\frac{T_0}{T}\right]^{3/2} \quad . \tag{6}$$

Insertion of Eq. (6) into Eq. (2), and use of the normalized time

$$\tau \equiv \delta\nu_0 t \quad , \tag{7}$$

and temperature

$$\tilde{T} = T/T_0 \quad , \tag{8}$$

derives the following equation for the fractional temperature change:

$$\frac{d\tilde{T}}{d\tau} = \frac{1 - \tilde{T} + E^2/E_p^2}{\tilde{T}^{3/2}} \quad . \tag{9}$$

Equation (9) is useful because it expresses the temperature change solely in terms of the ratio of the wave electric field to the characteristic plasma field. Although it must be solved numerically, E/E_p is the only parameter that need be varied. Such a solution set is given in Fig 10. It can be applied for any initial temperature or ambient collision frequency by using Eqs. (7) and (8).

As shown in Fig. 10, for weak fields where $E/E_p \ll 1$, the temperature approaches the maximum value given by Eq. (3) within two or three characteristic heating times. For stronger fields, a longer time is required because the collision frequency decreases with time. Thus the mean time between collisions increases with time. In all cases, it would appear adequate to leave the transmitter on for, say, five or six characteristic heating times.

Before using Eq. (3) to estimate the temperature change caused by an oblique wave, we compare the results in Fig. 10 to temperature changes measured at the Arecibo site.[5] In order to make that

comparison, we must select appropriate values for the electric field E, the characteristic field E_p, and the characteristic time t_0. That selection requires specifying the collision frequency f, the energy loss per collision δ, the ambient temperature T_0, and the wave angular frequency ω. Nighttime values pertaining to an altitude of about 300 km are indicative of the Arecibo conditions.

We assume the ions to be oxygen atoms, (thus $\delta = 2\ m/M = 6.8 \times 10^{-5}$). The ambient F-layer temperature at Arecibo was about 800 K and the electron density about 3.6×10^5 el/cm^3, from which we estimate the effective collision frequency to be about 720/sec. (Works done by Gurevich[1] and Ginzburg,[7] include discussions of these parameters.) The wave frequency was 5.4 MHz for the measurement considered in this report.

Insertion of the above parameters into Eqs. (2) and (5) gives a value of about 0.3 V/m for the characteristic field and 20 sec for the characteristic time. We estimate that the Arecibo heater delivered about 0.2 V/m to the F-layer. Figure 11 compares measured temperature changes with ones calculated using these values.

The nearly exact agreement between experiment and theory shown in Fig. 11 is fortuitous, because the ionospheric parameters are not exactly known and other equally reasonable parameters could have been used in the calculation. The collision frequency and thus the characteristic time is the least certain of the input parameters used. The characteristic field, which determines the magnitude of the temperature change, is reasonably accurate. Nonetheless, the very simple Eq. (3) provides adequate estimates of the achievable heating, provided the transmitter is left on for 60 to 80 sec.

TEMPERATURE CHANGES CAUSED BY OBLIQUE MODIFYING WAVE

To estimate the temperature change caused by the oblique wave, we use Eq. (3) to re-express the electric-field contours shown in Figs. 4 through 9 in terms of temperature. To do that, we recalculate the characteristic field by inserting the proper frequency and temperature in Eq. (2) and using a nominal temperature of 1000 K.

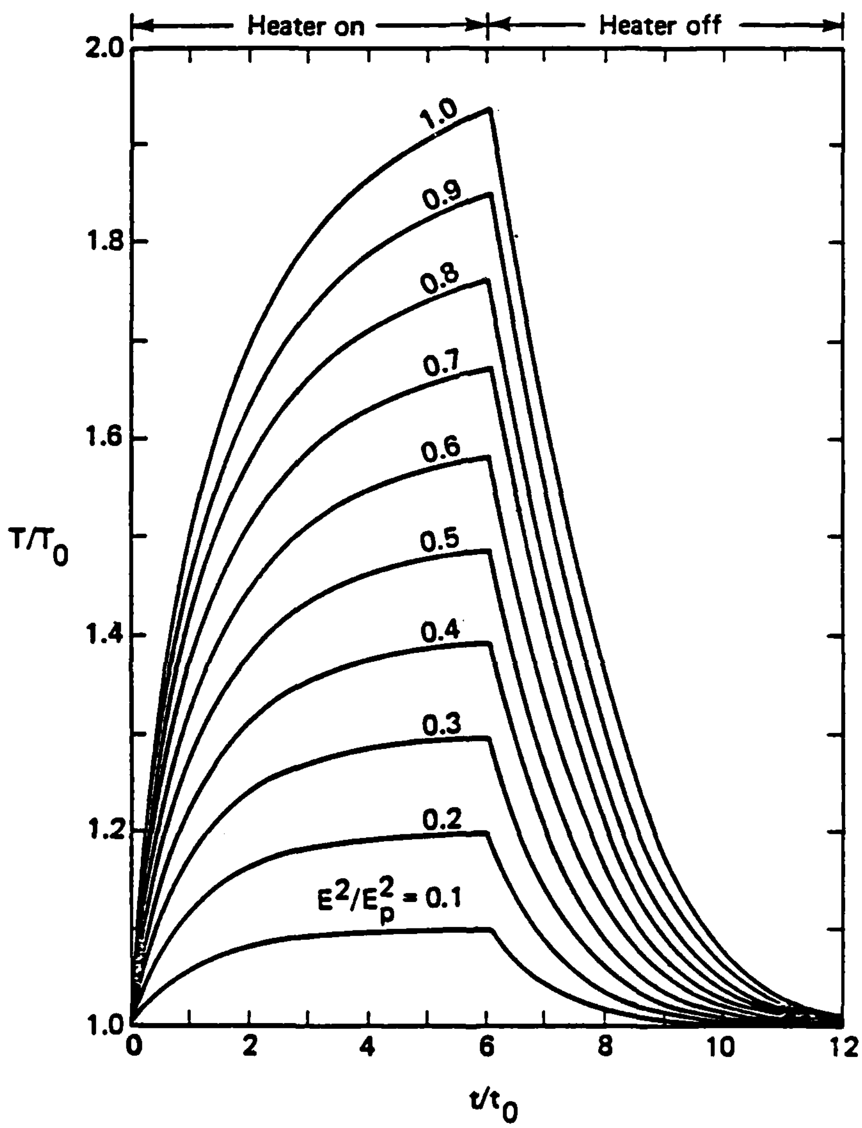


Figure 10. Fractional F-layer temperature change versus time for various electric field strengths.

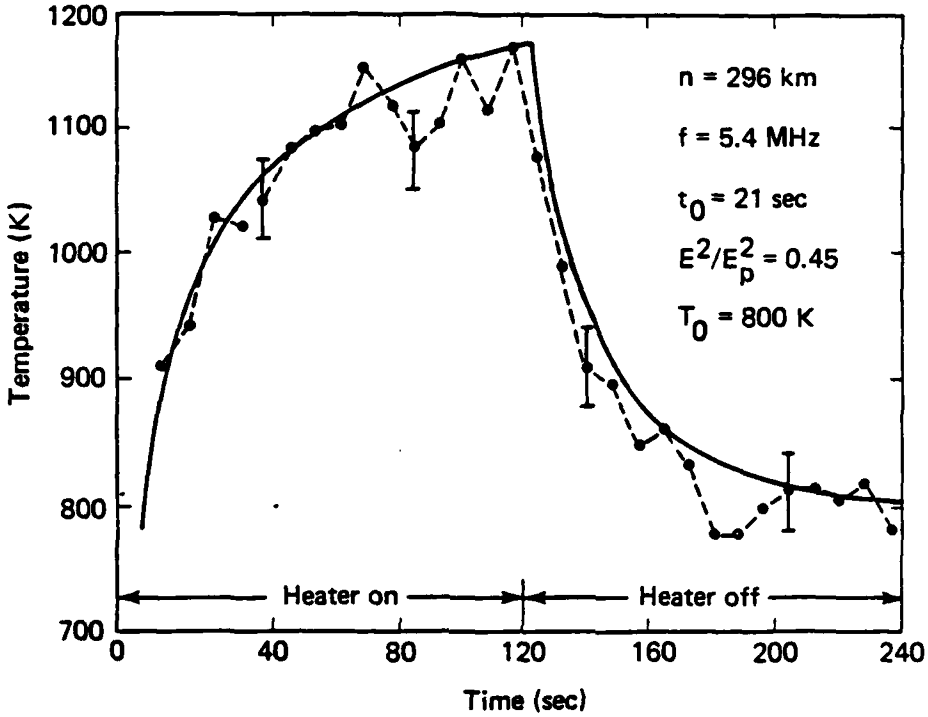


Figure 11. Comparison of calculated and measured electron temperature.

Figs. 4 through 9 show that the optimum frequency is about 13 MHz in the day and 9.5 MHz at night. That frequency dependence causes the heating to be more effective at night than in the day, despite the fact that the fields tend to be stronger in the daytime. That behavior occurs because the heating is governed by the square of the ratio of the wave field to the characteristic field. The temperature change, therefore, is inversely proportional to the square of the frequency [see Eqs. (2) and (3)].

Contours of estimated temperature changes for a frequency of 9.5 MHz and nighttime propagation are given in Fig. 12. The changes are substantial--several tens of percent or several hundreds of degrees--despite the fact that the assumed radiated power is only 100 kW and substantially greater powers would probably be used. Within the accuracy of the approximations made in this report, the induced temperature change is proportional to radiated power.

TRANSPORT PROCESSES

The results shown in Fig. 12 do not account for heat conduction or thermal diffusion, which will cause heat to flow from high-to-low-temperature regions. Those processes tend to smear out hot spots, such as the ones shown in Fig. 12. Mantas, Carlson, and LaHoz[5] give a detailed calculation of ionospheric heating including heat conduction produced by the Arecibo transmitter. That level of detail is not required for the present feasibility analysis. Therefore, we will make an order of magnitude estimate of the degree to which transport processes alter the contours shown in Fig. 12.

Our approach is to estimate the relaxation time of a localized heated region. If that time is long compared with the heating time given by Eq. (5), then heat conduction and diffusion will not strongly distort the calculated temperature-change profiles. If the relaxation time is short compared with the heating time, then the heat will diffuse away from the caustics. In that case, the small hot and cool regions illustrated in Fig. 12 will merge into a single, relatively uniform region characterized by an intermediate temperature.

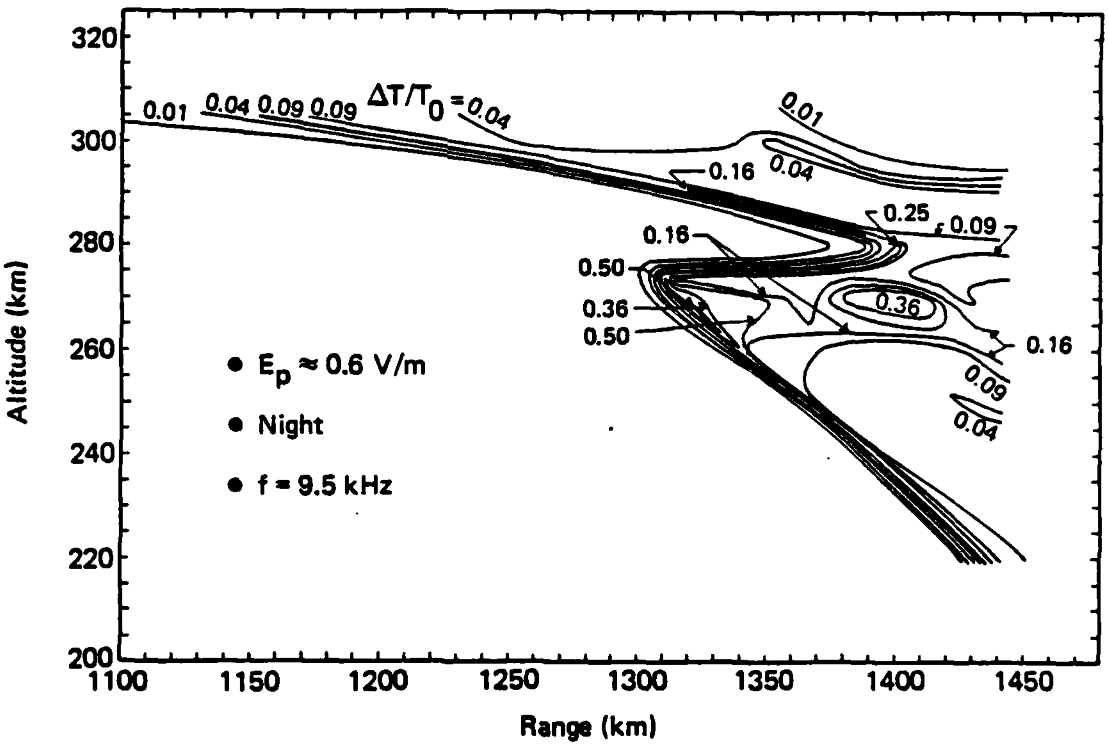


Figure 12. Calculated contours of electron temperature.

Landau and Lifschitz[8] show that the relaxation time τ_c for heat conduction is on the order of

$$\tau_c \sim L^2/\chi \quad , \tag{10}$$

where χ is the thermometric conductivity and L is the dimension of the heated region. The relaxation time for thermal diffusion is given by the same expression, provided that χ is replaced with the thermal diffusion coefficient D. We see from Eq. (10) that the relaxation time is much longer for large volumes than for small volumes. Transport processes smear out small hot spots, like those produced near the caustics of oblique waves, more quickly than large heated volumes, such as those produced by vertical modifying waves.

In work performed by Gurevich[1] it is revealed that χ and D are of the following order of magnitude:

$$\chi \sim D \sim \frac{5KT}{2m\nu} \sim 50\ \mathrm{km}^2/\mathrm{sec} \quad , \tag{11}$$

where we have used numerical values for T and ν typical of those that occur at night at altitudes near 300 km. Next, we compare the transport relaxation time, given by Eq. (10), with the characteristic heating time, calculated from Eq. (5) at around 20 sec in the nighttime F-layer. We make that comparison for a vertical modifying wave, like the one used at Arecibo, and an oblique wave, like the one used to calculate the results in Fig. 12.

The dimension of the ionosphere heated by the vertical Arecibo transmitter is on the order of 60 km.[5] If this value is inserted into Eq. (10), a relaxation time on the order of 70 sec is computed. This is somewhat shorter than the 120 sec duration of the Arecibo transmission (see Fig. 11), but about three times longer than the 20 sec characteristic heating time. Therefore, we would expect Eq. (9) to give results that are reasonably accurate but not precise. The close agreement between measured and calculated temperature changes shown in Fig. 11 fulfills that expectation.

The heated regions illustrated in Fig. 12 are much narrower than 70 km and therefore, the relaxation time for the oblique wave will be much shorter than the 70 sec time estimated previously. We estimate from Fig. 12 that L = 10 km for the oblique wave which, when inserted into Eq. (11) gives a value of about 2 sec for the relaxation time. Because that transport relaxation time is much shorter than the characteristic heating time, the ionosphere cannot support the strong temperature gradients shown in Fig. 12. Instead, the heat will redistribute itself over a volume of dimension

$$L^2 \sim \chi t_0 \quad , \tag{12}$$

where we have assumed L to increase via diffusion until $\tau_c > t_0$ (i.e., until the rate at which temperature decreases due to heat transport, is slower than the rate at which it decreases due to energy lost to ions via collisions). Insertion of numerical values into Eq. (12) derives L = 50 km indicating that the temperature increases shown in Fig. 12 should be averaged over regions having dimensions on the order of 100 km. That value agrees with the scale size estimated by Gurevich[1] to characterize thermal inhomogeneities in the mid-to-high-latitude F-layer.

By taking the spatial average of the temperatures given in Fig. 12, we conclude that a 100 kW oblique modifier transmitter that is operating at night, can cause a 10 to 20 percent increase in electron temperature--equivalent to a 100 to 200 deg increase--throughout an F-layer volume that has a scale size on the order of 50 km. More powerful transmitters will cause greater temperature increases in direct proportion to the radiated power.

III. PARAMETRIC INSTABILITIES

The original goal of ionospheric modification experiments was to alter the temperature and hence, the density of the ionosphere. A much wider variety of unexpected phenomena were observed and attributed to parametric instabilities triggered by the modifying wave. All of these instabilities have been studied intensely and are of great interest to researchers in nonlinear plasma physics.

This report concentrates on the manifestations of parametric instabilities that might affect the performance of HF/VHF communication or radar systems. Artificial generation of spread-F, wide-band absorption, and field aligned striations fall into that category. Enhanced airglow and upshifted and downshifted plasma line scattering observed on the 430 Mhz Arecibo radar are excluded. Although of great scientific interest, they are unrelated to HF/VHF systems.

One of the most important instabilities for ionospheric modification is the so-called parametric decay instability, which occurs only if a matching condition exists between the modifier wave frequency and the ionospheric plasma frequency. That condition, easily satisfied by a vertical wave, can never be satisfied by an oblique wave. This section identifies those phenomena that are manifestations of the parametric decay instability.

The conclusions of this report are based solely on information taken from results of vertical experiments and the meager available Soviet data on oblique modification experiments. The report concentrates on instabilities believed to have produced observable phenomena in vertical modification experiments. None of the many manifestations of instabilities observed in vertical modification experiments were predicted by plasma theory--all were unexpected and explained after the fact. We must therefore qualify the conclusions of Sec. III by noting that an oblique modification experiment could produce the same pleasant surprises as occurred for the vertical experiments. New types of instabilities could cause unexpected manifestations.

PARAMETRIC DECAY INSTABILITY

The parametric decay instability is by no means the only instability of interest in the study of ionospheric modification, but it is believed responsible for producing many of the phenomena observed during vertical modification experiments. As will be shown, it cannot be excited by oblique modifying waves. That study of the parametric decay instability is useful in determining which effects produced by vertical modifying waves can and cannot be excited by vertical waves.

Several authors apply the theory of the parametric decay instability to ionospheric modification.[9,10] In another work by Fejer,[11] a review that is particularly well-suited to the present analysis is given. For that instability, the modifying wave acts as a pump that excites a Langmuir wave of frequency ω, which is given by

$$\omega_1 \approx \omega_p \left[1 + \frac{1}{2} \left\{ \frac{\omega_c^2}{\omega_p^2} + 3k_1^2 \lambda_D^2 \right\} \right] \quad , \tag{13}$$

and an ion acoustic wave whose frequency is on the order of

$$\omega_2 \approx \frac{m}{M} \omega_p \quad ,$$

where ω_p is the electron plasma angular frequency, ω_c is the gyrofrequency, λ is the electron Debye radius, k_1 is the wave number of the Langmuir wave, and m and M are the electron and ion mass, respectively. Note also that

$$\omega_c^2/\omega_p^2 \ll 1 \quad , \tag{14a}$$

and, for waves that propagate without prohibitive Landau damping,

$$k_1^2 \lambda_D^2 \ll 1 \ . \tag{14b}$$

Under the above conditions, ω_1 closely approximates the upper hybrid frequency.

In order for the parametric decay instability to be excited, the following condition must be satisfied:

$$\omega_M = \omega_1 + \omega_2 \approx \omega_p \left[1 + \frac{1}{2}\, \omega_c^2/\omega_p^2\right] \quad , \tag{15}$$

where ω_M is the angular frequency of the modifier wave. The above equation shows that for the modifying wave to excite the parametric decay instability, its frequency must be nearly equal to the upper hybrid frequency, which is slightly higher than the plasma frequency.

For a vertical modifying wave, the ordinary wave satisfies the above frequency matching condition, but the extraordinary does not. That behavior occurs because vertical waves that are reflected from the ionosphere satisfy the following relations:

$$\omega \geq \omega_p \qquad \text{for O-wave} \quad , \tag{16a}$$

$$\omega \geq \omega_p \left[1 + \frac{\omega_c}{2\omega_p}\right] \qquad \text{for X-wave} \quad , \tag{16b}$$

where the equality applies at the reflection height. The ordinary wave satisfies the frequency matching condition given by Eq. (15) just below the reflection height; whereas, the extraordinary wave can never satisfy that condition. Similarly, oblique waves that are reflected from the ionosphere satisfy the following relation:

$$\omega \geq \omega_p/\cos\theta >> \omega_p \tag{17}$$

where θ is the incidence angle and, as before, the equality applies at the reflection height. An oblique wave can never satisfy the frequency matching relation required for excitation of the parametric decay instability.

The above relations provide a simple criterion for determining which effects produced by a vertical modifier wave can and cannot be produced by an oblique wave. Specifically, any effect occurring when a vertical transmitter was polarized in the ordinary mode and vanishing

when the polarization was changed to the extraordinary mode was probably caused by the parametric decay instability. Therefore, it could not be excited by an oblique modifier wave. Phenomena that do not vanish when the polarization is changed from ordinary to extraordinary could perhaps be generated with an oblique wave.

We apply that criterion to three phenomena that have been observed during vertical modification experiments and which, if excitable with an oblique wave, have implications for HF/VHF military systems.

FIELD ALIGNED STRIATIONS

One of the unexpected effects noted during experiments with the Plattville heater, was the production of a cloud of short-scale irregularities that were aligned along the geomagnetic field.[12] More recently, such irregularities have been produced at Tromso, Norway.[13] Scattering in HF/VHF from such irregularities is concentrated strongly in directions that correspond to specular reflection from geomagnetic field lines.

Barry[14] demonstrated that scatter from man-made field-aligned irregularities offers a means of achieving over-the-horizon communication at VHF frequencies. Although links dependent on aspect-sensitive scattering would provide only localized coverage, they would be inaccessible to most jammers.

Such irregularities also could, if produced by an oblique wave, cause unwanted deleterious effects. For example, a powerful high-latitude backscatter radar could cause self clutter by generating irregularities along field lines oriented nearly perpendicular to the propagation path. In principle, one could also cause clutter on an enemy's radar, although geometric constraints appear to make that application impractical.

A goal of our present research is to determine whether applications such as those just mentioned are feasible with an oblique modifying wave. Unfortunately, the evidence suggests that they are not. Fejer[11] and Fialer[12] report that short-scale irregularities are

formed only when the transmitter operates in the ordinary mode and below the critical frequency in the F-layer.

Hedberg, et al., give data that are even more substantial.[13] They ran tests in which backscatter from field-aligned striations was monitored as the polarization of the modifying transmitter was repeatedly switched between ordinary and extraordinary modes. In every case in which backscatter was observed during O-mode operation, that backscatter vanished when the polarization was switched to X-mode operation. They attribute that behavior to the fact that only the O-mode can reach the altitude at which the frequency of the modifying wave equals the upper hybrid frequency of the local ionosphere, thus satisfying the matching condition derived by Eq. (15). It is also pointed out that, under their propagation conditions, the X-mode is usually more heavily absorbed in the lower ionosphere than the O-mode.

As discussed previously, an oblique wave is even less capable of reaching the altitude where the frequency matching condition could be satisfied than a vertical X-mode wave. Of course, oblique waves are more heavily absorbed than vertical ones. Available evidence indicates that short-scale field-aligned striations (and the associated aspect-sensitive scatter) cannot be produced with an oblique modifying wave.

WIDE-BAND ATTENUATION

Wide-band attenuation is an exception to the usual experience of being able to increase received signal amplitude by increasing the radiated power of the transmitter. When wide-band attenuation is operative, there exists an optimum transmitter power. Greater radiated powers will reduce a signal received through the ionosphere. The implications of wide-band attenuation are obvious and widely appreciated. This report assesses whether wide-band attenuation would be expected to affect oblique signals as well as vertical ones.

Wide-band attenuation was observed first at the Plattville site.[2] It caused strong anomalous attenuation on a vertical diagnostic wave that penetrated an F-region volume heated by a powerful vertical modifying wave. The effect was observed only when both the diagnostic

and modifying waves were transmitted in the O-mode and the frequency of the diagnostic wave was a few tens of kilohertz below the frequency of the modifying wave.

Subsequently, Kopka, et al.,[15] measured wide-band absorption on the modifying wave itself. In those self-absorption experiments, the amplitude of the reflected wave was monitored as the power of the transmitter was increased stepwise to very high values. Beyond a certain point, the amplitude of the reflected wave decreased as the transmitter power increased, thus demonstrating a nonlinear action in which the modifying wave altered the ionosphere in a way that limited the power of the received signal. Again, the effect occurred with a vertical modifying wave in the O-mode, but not in the X-mode.

Although all details of the generation mechanism are not well understood, wide-band attenuation is usually attributed to scattering of HF waves into Langmuir waves by field-aligned, short-scale, striations.[11] The discussion of whether field-aligned striations could be produced by an oblique modifying wave also applies to wide-band attenuation. However, current evidence suggests that neither effect could be so produced.

ARTIFICIAL SPREAD-F

The most consistent ionospheric modification phenomenon observed in conjunction with vertical heaters is also one of the least understood. It is the production of an effect indistinguishable from naturally occurring spread-F. The striations that cause artificial spread-F tend to be field aligned and, therefore, reminiscent of the short-scale striations previously discussed.[16] Unlike those striations, however, the ones responsible for artificial spread-F occur regardless of whether the heater used O-mode or X-mode illumination.[2] Fejer points out that controversy exists with the role that several types of instabilities might play in the production of artificial spread-F.[11] At present, there is no reason to conclude that artificial spread-F could not be produced by an oblique modifying wave.

IV. SOVIET EXPERIMENT ON IONOSPHERIC MODIFICATION WITH OBLIQUELY INCIDENT WAVE

To our knowledge, a Soviet experiment is the only one to date that has used an oblique modifying wave. It is described in a series of articles by Bochkarev, et al., published between 1979 and 1982.[17-20] This section briefly summarizes and interprets those results in terms of the analysis given in Secs. II and III.

The information contained in Bochkarev's papers is incomplete and, in some cases, contradictory. The modifying wave apparently was launched from a transmitter having a gain of around 100 kW (20 dB) and a radiated power of 200 kW, which corresponds to an effective power of 20 MW--about four times the 5 MW effective power (17 dB gain, 100 kW radiated) used to calculate the contours in Fig. 12. Some measurements were made at a frequency of 5.75 MHz; so from Eq. (2) it can be inferred that the characteristic plasma field E_p was less than the 0.6 V/m that pertains to Fig. 12. The ionospheric conditions under which the Soviet experiments were performed are not known, but the more powerful transmitter and smaller E_p indicates that the ratio E^2/E_p^2, and thus the temperature change, was probably several times greater than shown in Fig. 12.

The main interaction region for the Soviet experiments was centered about 900 km from the transmitter and about 200 km above the ground. Because of the relatively low frequency, those distances are shorter than the 1400 km range and 270 km height at which the interaction region shown in Fig. 12 is centered.

As discussed in Sec. II, an oblique modifying wave deposits energy near its caustics which then spreads via heat conduction over a region having a dimension of perhaps 50 km. Therefore, in an oblique modification experiment care must be taken to ensure that the diagnostic wave intersects the ionospheric region affected by the modifying wave. Bochkarev solved that problem by transmitting the diagnostic wave and the modifying wave at nearly the same frequency, thereby

guaranteeing that both signals would traverse nearly the same path and, therefore, that the diagnostic wave would pass through the caustic of the modifying wave.

Bochkarev reports that the amplitude of the diagnostic wave doubled within a few tens of seconds after the modifying wave was turned off, and its vertical angle of arrival changed by 2 or 3 deg.[20] No mention is made of the action of the modifying wave on itself.

Our analysis of the propagation implications of oblique heating is not complete and is beyond the scope of the present interim technical report; those results will be reported at a future date. However, we conclude from the above discussion and the results given in Fig. 12 that the Soviet experiment could easily have raised the temperature of the F-layer by a few hundred degrees. It is not surprising that a wave passing through such a heated region would suffer the perturbations reported by Bochkarev.[17-20]

V. CONCLUSIONS

Full-wave calculations show that a transmitter with a power-gain product on the order of 10 MW can launch an oblique wave strong enough to produce electric fields of several tenths of a volt per meter or more in the ionosphere. Such fields are comparable to the characteristic plasma field and produce substantial increases in the electron temperature. Those temperature increases are initially concentrated near the caustics, which occur in the F-layer beyond the midpoint of the propagation path. The energy thus deposited quickly spreads via heat conduction and, within a few tens of seconds, raises the temperature of a volume having a dimension of about 50 km by perhaps a few hundred degrees. The heating is somewhat more effective at night than in the daytime.

Our analysis of the propagation implications of such an artificially heated volume will be reported in the future. However, a preliminary assessment indicates that an HF signal that traverses the heated region will undergo changes in amplitude and angle-of-arrival that are detectable on the ground. Such effects were measured during Soviet ionospheric modification experiments that used an obliquely incident modifying wave.

The prognosis for using an obliquely incident wave to trigger nonlinear effects normally attributed to parametric instabilities is poorer than the prognosis for producing measurable heating-induced effects. Such waves cannot satisfy frequency-matching conditions required for generation of the parametric decay instability. Therefore, a number of effects produced by vertical modifying waves, which can satisfy the frequency matching conditions, cannot be produced by oblique waves. Such effects include wide-band absorption and aspect-sensitive scattering from short-scale, field-aligned striations. However, oblique waves might be capable of producing artificial spread-F. It must be mentioned that all instability-induced phenomena observed during vertical modification experiments came as a surprise.

None were predicted by plasma theory, which was applied later in order to explain the observations.

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